Data Analysis of a Space Equipment: Common Software Tackles Uncommon Task

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Data Analysis of a Space Experiment: Common Software Tackles Uncommon Task

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Presented here are the software adaptations developed by laboratory scientists to process the space experiment data products from three experiments on two International Microgravity Laboratory Missions (IML-1 and IML-2). The challenge was to accommodate interacting with many types of hardware and software developed by both European Space Agency (ESA) and NASA aerospace contractors, where data formats were neither commercial nor familiar to scientists. Some of the data had been corrupted by bit shifting of byte boundaries. Least-significant/most-significant byte swapping also occurred as might be expected for the various hardware platforms involved. The data consisted of 20 GBytes per experiment of both numerical and image data. A significant percentage of the bytes were consumed in NASA formatting with extra layers of packetizing structure. It was provided in various pieces to the scientists on magnetic tapes, Syquest cartridges, DAT tapes, CD-ROMS, analog video tapes, and by network FTP.

In this paper I will provide some science background and present the software processing used to make the data useful in the months after the missions.
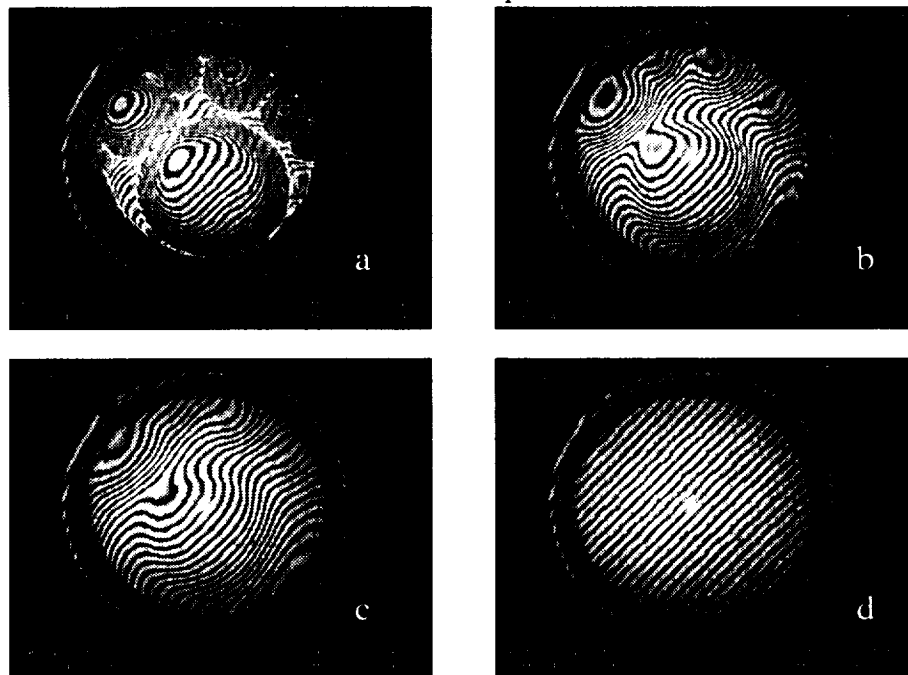
1 The Experiment

The experiments were focused on using interferometry to follow the full-field time evolution of the density of liquid-vapor critical fluids[Wilkinson 1997]. Figure 1 provides an impression of the images we worked with. Near the critical point, pure fluids are very compressible, and density is very easily disturbed. In addition the time to equilibrate the density diverges as one approaches the critical temperature. Our goal was to quantify the time constants for expected diffusive exponential relaxation to equilibrium.

In the Earth's gravity, g_0, density relaxation is greatly influenced by buoyant convection of the inhomogeneous density domains[Boukari 1995, Zappoli 1996, Zhong 1995]. That limitation, in part, motivated this experiment to be executed

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Figure 1: Sequence of interferograms for a relaxation event that started from the bubble and drop configuration of a two-phase state. These images reflect the relaxation of the residual density inhomogeneity after the thermostat has stabilized at 8.4 mK above the critical temperature.

in space on-board the shuttle, where the dc gravity level was approximately $10^{-6}g_0$ and the vibration level was less than $10^{-3}g_0$.

Experiments with substances at or near their liquid-vapor critical point present demanding metrology challenges. For example, the required thermostat provided temperature control in the vicinity of 45 °C with a stability of ±50 μK. There were also optical alignment issues that would require more discussion than is possible here.

Critical points have had a profound history in thermodynamics and statistical mechanics. It started with Andrews observation in 1869 that CO_2 at roughly 31 °C and 73 atmospheres became milky white[Andrews 1869]. It has been found since, that all pure fluids, if they are chemically stable, at a unique temperature and pressure for each fluid, exhibit the same behavior. Many thermophysical properties of fluids either approach infinity or become vanishingly small at critical points. Some examples are infinite heat capacity, thermal conductivity, compressibility, thermal expansion, and bulk and shear viscosities.

At the same time fluids have vanishing thermal diffusivity, surface tension, latent heat, and speed of sound. The theory of this special phase transition has a foundation in common with the ferromagnetic, super-fluid, and super-conducting phase transitions. The universality of this behavior continues to stimulate research.

2 Analysis

The post-mission analysis entailed 1) plotting apparatus function for the seventy six hours of operation per experiment to be sure that thermal and optical behavior was satisfactory, and 2) converting interferometric digital video images into optical phase maps. The apparatus numerical data consisted of temperature readings, light intensity levels, detector settings, and engineering status parameters. It was sampled once per second, generating four variably interleaved packets totalling ~1800 bytes/second. The image data was sampled every six seconds with 512x512 pixels at 6 bits per pixel in black and white. One six second image file consisted of 262,164 bytes. Other bytes were generated by NASA packetizing protocols.

2.1 Numerical Data

Numerical data conversion and plotting was done in the programming environment called GAUSS[1], a text based matrix language with useful canned functions and plotting graphics. Given the quantity of data GAUSS' virtual memory capability was necessary. This work started when the scientists were working on DOS PC's with 64 MB of RAM, which GAUSS used well. Today the author works on a PC with LINUX, where GAUSS continues to be a workhorse.

The main part of the apparatus function data analysis was to dissect the byte and bit-wise information from the unfamiliar file format generated by the experiment apparatus and reformatted by NASA during transmission. One or more hour long log files were read in as HEX bytes, unique packet header bit patterns were found and indexed at byte addresses, and, using discrete byte offsets from the packet headers, the bytes of the variables of interest were captured using string operations. There were 46 variables of interest with 1, 6, 8, 11, 16, 21, and 32 bit sizes. Each packet was time encoded since not all packets came each second, nor in the same time order within a second. Also, not all packets were intact, so fault tolerance was needed to recognize and discard defective packets. That fault tolerance required the code to handle missing values while not discarding stray data that was real. The fault tolerance was not *a-priori* defined. So iterative code development on real post-mission data was required. Some bit variables (status flags) were used to indicate range levels needed to quantify other variables, thereby coupling variables from different packets. Time was encoded as 11 bits to represent the universal time code (UTC = GMT) day, and 21 bits to represent UTC seconds in the day. For the

scientific users it was necessary to convert that time into mission elapsed time (MET) and experiment run time (ERT) for all data packets. Other variable formats were "number unsigned word", "number unsigned double word", and "number signed double word". Two's complement arithmetic was used on the latter format. In the end IEEE single precision floating point and ASCII files were created for plotting and sharing with co-investigators. The array operators of GAUSS greatly condensed the syntax needed to write this code.

2.2 Image Data

The first stage of image processing required converting the mission data format into a format suitable for image processing and moving all image files to a massive NFS mountable file-server. In an image each pixel's intensity was stored in 8 bits, where 2 bits were locked values. A single image contained packet header ID bytes, 22 bytes of ASCII information to correlate an image with science, and then all the odd raster lines followed by all the even raster lines. The image data exhibited the bit shifting of byte boundaries. A veteran hacker, Bob Perry, at NASA Lewis wrote some mixed C and assembly codes to perform bit shifts until image packet header ID bytes became visible, then stripped NASA packetizing structures (which could occur in the middle of an image), and finally created one file per image with a time code for the file name. Next PV-Wave[2] was used to view images confirming their quality and create files that could be input into the commercial lens makers' testing software called FAST V/AI[3]. FAST V/AI was used to convert interferograms into optical phase maps. It automatically found fringe centers, which are contours of constant phase, assigned fringe orders, and used cubic spline interpolation to establish phase values on a square array. (Today we do phase shifting interferometry with our own C code for the intensity to phase conversion task.) After the conversion to optical phase map arrays, GAUSS code was used to complete the analysis. The following analysis of optical phase maps was more computational and less string and byte manipulation intensive.

Typically twenty five two-dimensional arrays (phase maps) were created from FAST V/AI to span each experiment event, ranging from forty minutes to seven hours during the space experiment. In GAUSS the last phase map was array subtracted from each of the earlier phase maps. These difference maps reflect the deviation of the fluid density from equilibrium, (see Figure 2). The difference maps were linear least squares fit to a linear combination of circular Bessel functions of the form

$$\delta(r,\theta,t) = A_0(t)f_0(r) + \sum_{a=1}\sum_{b=1}[B_{ab}(t)sin(a\theta) + C_{ab}(t)cos(a\theta)]J_a(k_{ab}r), \quad (1)$$
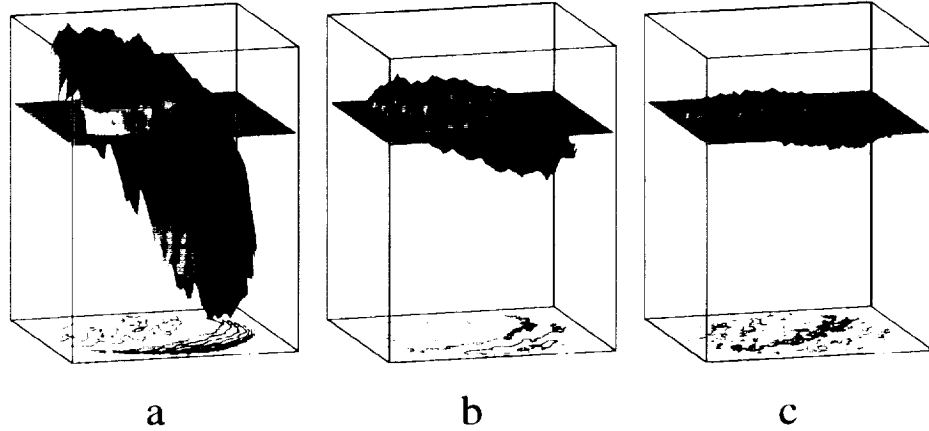
where

$$f_0 \equiv J_0(k_{01}r) - \langle J_0(k_{01}r)\rangle \quad (2)$$

Figure 2: Time sequence of difference phase maps that are fit to the linear combination of Bessel's functions. The surfaces are directly related to the fluid density deviation from equilibrium.

<div align="center">a   b   c</div>

represents a mass conserving form of the J_0 mode. Mass conservation was a physical constraint because the fluid sample was a closed cell. The coefficients A, B, and C contained the time dependent weighting factors of the eigenmodes of the thermal diffusion problem[Berg 1993]. Those time sequences of coefficients were then non-linear least squares (maximum likelihood) fit to an exponential of the form

$$\{A(t), B(t), C(t)\} = K + H \left\{ e^{(-t/\tau)} - e^{(-t_{ref}/\tau)} \right\}. \qquad (3)$$

The t_{ref} accounted for the fact that the final image may not have been at the fluid equilibrium state even though the experiment run durations were roughly 5 time constants. K allowed for a possible noise offset in the sequence of coefficients. K typically was two to three orders of magnitude smaller than H. See Figure 3.

This work was the first quantitative confirmation that classic heat diffusion describes the long time equilibration of the unusual critical fluids as close as 1 mK to the critical temperature. Such a confirmation was not possible in Earth's gravity.

3 Acknowledgements

The author would like to express his gratitude to the hundreds of people in NASA and ESA who found a way to work together over great distances to make this space experiment happen. Especially appreciated are the colleagues that authored reference [Wilkinson 1997]. They afforded a perseverance to this work that is uncommon.

Figure 3: Example of the time relaxation of some density modes and their exponential fit to Eqn. 3.
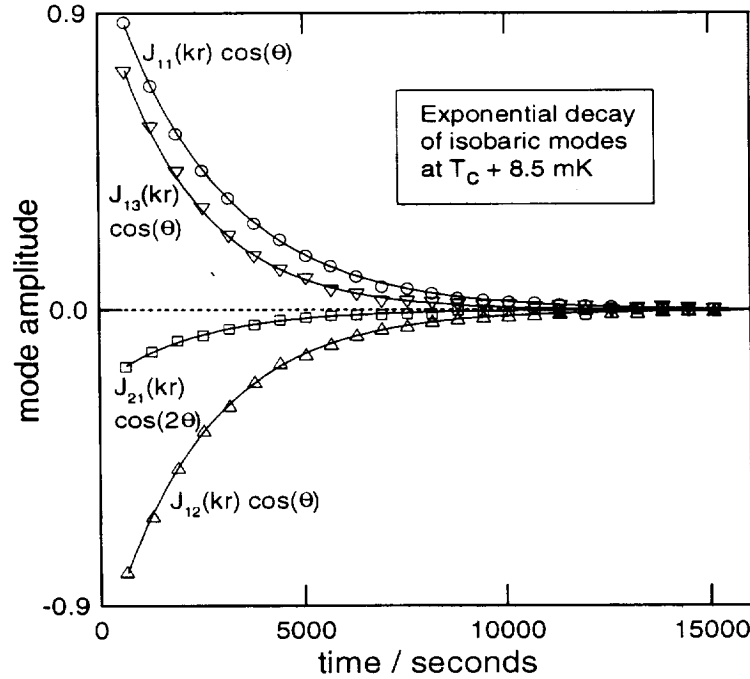
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